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Motor Origins of Tool Use

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The current study examines the developmental trajectory of banging movements and its implications for tool use development. Twenty (6- to 15-month-old) infants wore reflective markers while banging a handled cube; movements were recorded at 240 Hz. Results indicated that through the second half-year, banging movements undergo developmental changes making them ideally suited for instrumental hammering and pounding. Younger infants were inefficient and variable when banging the object: Their hands followed circuitous paths of great lengths at high velocities. By 1 year, infants showed consistent and efficient straight up-down hand trajectories of smaller magnitude and velocity, allowing for precise aiming and delivering dependable levels of force. The findings suggest that tool use develops gradually from infants' existing manual behaviors.

How do children learn to use the tools of their culture? Children begin to show an increase in the use of tools in the 2nd year (McCarty, Clifton, & Collard, 2001), but despite the ubiquity and importance of tool use in human culture, its ontogeny is not well understood. Theories on the development of tool use in humans have often emphasized the emergence of new forms of means-end thinking and the achievement of insight (Bates, 1979; Piaget, 1952). Tool use in this view is the product of a developmental shift to a more advanced form of representational thinking, which leads children to gain causal understanding of a task.

Reports of tool use in nonhuman animals and humans suffering from ideational apraxia challenge the notion that causal understanding is a necessary prerequisite for tool use, however. There have been numerous demonstrations of tool use in many nonhuman animals such as capuchins, chimpanzees, gorillas and crows (Boesch-Achermann & Boesch, 1993; Breuer, Ndoundou-Hockemba, & Fishlock, 2005; Fragaszy & Visalberghi, 1989; Weir, Chappell, & Kacelnik, 2002), despite their less advanced cognitive capabilities relative to those of humans. Casting further doubt on cognitive accounts of tool use have been findings from patients with ideational apraxia (Ochipa, Rothi, & Heilman, 1989). These patients are incapable of naming tools or their functions, yet show no deficit in the usage of a tool.

The evidence from comparative psychology and ideational apraxia suggests that cognition is not the sole, and probably not even the most important, factor that underlies simple forms of tool use. Perception-action theorists have argued that the same is true for the ontogeny of tool use behaviors in infancy and toddlerhood. According to perception-action theory, early instances of tool use need not require insight, but instead can develop from infants' and toddlers' exploratory activities and perception-action routines (Lockman, 2000). In this view, simple tool use develops in a more continuous fashion from infants' existing motor activities and does not require a qualitative shift to an advanced form of representational thinking.

In this connection, young infants already show repetitive motor patterns that appear quite similar in certain respects to later appearing skills (Piek & Carman, 1994; Thelen, 1981). Several investigators have proposed that these early repetitive behaviors enable infants to couple perceptual and motor information and that these behaviors serve as a substrate from which more skilled actions develop (Goldfield, 1995; Lockman, 2000; Thelen, 1981). Practicing early motor behaviors is especially important because the development of neural tracts innervating skeletal muscle in mammals is crucially dependent on activity (Jansen & Fladby, 1990). Furthermore, the emergence of complex movements does not rely on activation of single muscles, but depends on the tuning of specific motor synergies (Grillner, 1985; Sporns & Edelman, 1993).

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One example of early repetitive motor behaviors becoming incorporated into skilled action comes from the domain of locomotion. Thelen and Fisher (1982) showed that the muscle synergies underlying infants' spontaneous kicking while in a supine position and stepping while being held upright were identical, suggesting that the two behaviors were in fact the same, except for the differing influence of gravity. In a subsequent study, Thelen and Ulrich (1991) considered the development of this movement pattern throughout the 1st year and concluded that it serves as a substrate for the emergence of skilled locomotion.

In a related vein, in the domain of manual behaviors, we posit a developmental connection between banging and later forms of percussive tool use based on the surface similarity of the action patterns. Specifically, we ask whether banging movements, defined as repetitive up and down motion of the arm with an object in hand, are the motor building blocks of some basic tool use behaviors such as pounding and hammering. Banging movements become prevalent starting around 6 months and continue to be frequent over the next few months, with some studies showing a decrease in this behavior toward the end of the 1st year (Palmer 1989; Thelen, 1981).

One approach for understanding how early motor behaviors become integrated into skilled action comes from a set of theories collectively referred to as minimum theories. Minimum theories arose from the observation that despite the infinite number of movement choices that humans have, certain movement solutions tend to be far more attractive than others and thus humans perform most simple motor tasks almost exactly alike (Flash & Hogan, 1985; Hogan, 1984). Performance of these movements becomes more similar both within and across participants with extended practice, suggesting that the early phase of task acquisition is used to explore possible movements and find an optimal solution, and the later phase would be characterized by perfecting the chosen movement pattern (Uno, Kawato, & Suzuki, 1989). Although no single theory has yet explained why a particular "attractive" motor solution is selected, there is consensus that humans typically choose motor solutions that are efficient, reduce muscular exertion, and avoid uncomfortable postures (Engelbrecht, 2001).

We suggest that minimum theories are also useful for understanding how the early repetitive motor behaviors of infants can become transformed into more skilled forms of action that can be recruited for tool use. Young infants who are just beginning to master simple motor tasks often exhibit a great variety of movements and only show more adaptive, and efficient movements with practice (Adolph & Berger, 2006). This implies that infants explore many possible solutions to accomplish any given motor goal and through repeated practice select an efficient one (Sporns & Edelman, 1993). Similar gains in efficiency characterize skilled tool users. Research with adults has shown that stone knappers with high levels of expertise exhibit very efficient hammering movements within a relatively consistent range of motion (Biryukova & Bril, 2008).

In the present investigation, we focus on the early development of banging—a common but understudied form of infant manual behavior—and the implications of developmental changes in this behavior for tool use. Banging appears similar to hammering in terms of its overall form, but for the absence of a localized target. For banging to serve as a foundation of later percussive forms of tool use, however, several important motor criteria need to be fulfilled. Specifically, hand movements need to be predictable and consistent, enable the best possible aim, and employ velocities that deliver an appropriate and consistent amount of force. We suggest that in typical motor development as a result of extended practice, banging begins to fulfill all the preceding criteria and thus becomes well suited for pounding and hammering. We investigated these possibilities by presenting infants with tool-like objects that resembled hammers and studied developmental changes in the motor organization of their banging, using high-speed kinematic recordings.

Method

Participants

Twenty (13 male infants) infants between the ages of 6.4 and 14.7 months (M = 299 days, SD = 80 days) participated in the current study. We chose to sample across age continuously to have the ability to detect possible nonlinear development trends. Two of the infants were African American, 2 were Hispanic, and 15 were Caucasian. One infant had multiple ethnic and racial backgrounds. Informed consent was obtained from the infants' parents. Families received a small toy for participation.

Equipment and Procedure

Families visited the lab for a single visit that lasted approximately 15 min overall. Infants were seated on their parents' laps in front of a tabletop surface and parents were asked to hold infants around the hip to provide a stable base of support while also allowing free range of motion of the upper body. At this point, reflective markers were placed on the infant, taking breaks as needed so that the infant did not become fussy. Infants were then repeatedly presented to the left or right hand with a 2.5 cm (1 in.) cube attached to a 14 cm (5 in.) handle to elicit banging behaviors with each hand; the order of presentation to the different hands was randomized. If infants did not spontaneously bang researchers would use a 2.5 cm (1 in.) wooden cube to elicit noise by tapping it slightly on the table to encourage children to bang, the researcher ceased tapping the object immediately if infants started to bang. Testing ended when infants became fussy or had lost interest in the task.

Kinematic measures were recorded using eight Qualisys ProReflex240 cameras at 240 Hz (Qualisys AB, Gothenburg, Sweden). The cameras were placed in a semicircle around the tabletop to allow simultaneous recording of both arms as well as the torso. With hypoallergenic tape, 11 passive reflective markers were placed on the infants' upper bodies (see Figure 1). The marker placement is a slightly simplified version from that suggested by Wu et al. (2005) due to the special difficulties associated with the recording of infants' kinematics. Some infants would continually remove markers from the arm and were fitted with nylon sleeves that had the reflective markers glued to them at the corresponding bony landmarks of the arm. Bouts of banging were also recorded using one video camera at 30 Hz (Sony HandyCam, Sony Corporation, Tokyo, Japan). The video camera was facing the infants and linked directly to the Qualisys software allowing for time-synced recordings.

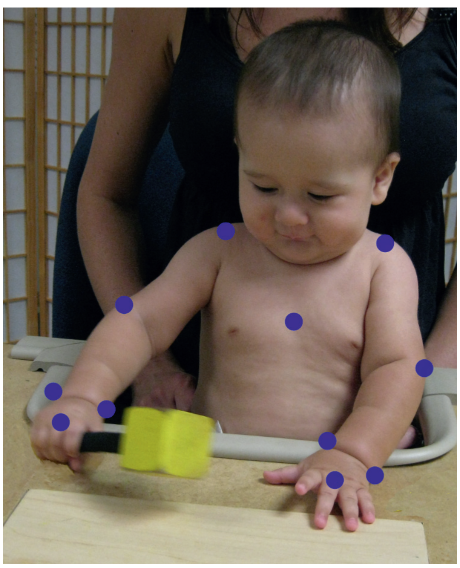

Figure 1. The figure illustrates the placement of all eleven markers on the infant: one at the xyphoid process (sternum) and five on each arm at the following locations: acromioclaviculare (shoulder), lateral epicondyle (elbow), radial styloid (wrist), ulnar styloid (wrist) and third metacarpal (knuckle).

Kinematic Data Analysis and Computational Methods

Review of the videotapes indicated that banging behaviors occurred in bouts of several strikes, a bout was defined as multiple uninterrupted strikes with the object. Each bout was subsequently divided into single strikes that serve as the basis for all analyses. The exact starting and ending points of each strike were determined based on the kinematic data and defined as the points when the marker on the knuckle of the active hand began (or stopped) moving vertically. If the ending of a strike was more than 500 ms prior to the beginning of the next strike, it was considered the end of the bout. Because we are interested in banging as a precursor to hammering, we only included strikes in the analysis during which infants held the object by the handle.

The trajectories for all markers were identified using the Qualisys software (QTM Track Manager, Qualisys AB, Gothenburg, Sweden) and then exported to MATLAB for further processing. Any missing data were interpolated using a cubic spline, the largest gap to be interpolated consisted of two frames. To eliminate measurement error, trajectories were then smoothed using a least squares spline approximation.

Results

Minimum theories predict that movements become more efficient and consistent with practice. We thus focused on three variables to address developmental changes in the efficiency of the spatial and temporal aspects of hand trajectories during exploratory banging: (a) the distance traversed by the hand, (b) the straightness of the hand trajectory, and (c) the velocity of the hand. To address changes in consistency or variability as a function of age for each of the preceding variables, we also analyzed developmental changes in the amount of variance about the mean. Lastly, we calculated a measure of within bout consistency—more precisely, how similar infants' hand trajectories were for sequential strikes within a bout of banging.

Across infants, the overall number of strikes ranged from 5 to 45. To reduce undue influence in the analyses by any one child with very high numbers of strikes, we chose to include the first 15 strikes from each infant. Based on these 15 strikes, the number of recorded bouts for infants ranged from 1 to 5 (M = 2.6 bouts) and the number of strikes ranged from 5 to 15 (M = 10.65 strikes). The number of strikes per bout ranged from 1 to 15 (M = 4.18 strikes per bout). We included a total of 213 strikes (recorded at 240 Hz) from the 20 infants when they were holding the object by the handle with either hand (134 right-handed strikes). Most infants used a single hand exclusively (18 of 20, 11 right hand only).

We used mixed-effects modeling for all analyses to regress each dependent variable onto age. We included a fixed effect for age and a random effect (intercept) for the participants in our model to allow for variations in development apart from age. We also included a blocked compound symmetry matrix to account for the repeated measurements for each infant (Pinheiro & Bates, 2000). In addition, we examined the developmental changes in consistency of hand trajectories by explicitly modeling error variance as a function of age (measured in days) in all analyses, allowing us to determine whether infants become more or less variable as they become older. The exact function included in each analysis was: $\mathrm{Var}(\varepsilon) = \sigma^2 \times \mathrm{Age}^{2\delta}$, where the value of δ would specify the relation between age and error variance. Negative values indicate a decrease of variability with age, for example $\delta = -.5$ would signify a linear inverse relation between age and variance. Because δ is a model parameter, it is possible to use standard statistical hypothesis testing to examine changes in variability as a function of age. Statistical analyses were performed using the nlme (Pinheiro & Bates, 2000) library in R.

Traversed Distance

Younger infants traversed far greater distances on a given strike than their older counterparts. To illustrate, the hand trajectories of the young infant in Figure 2a cover far more distance than those of the older infant in Figure 2b. Figure 3a shows that the predicted traversed distance for a 7-month-old infant was about 35 cm, whereas that of a 13-month-old infant was less than half as much at 16.5 cm. In addition, both figures show that younger infants exhibited greater variability in the amount of distance traversed than the older infants.

These patterns were confirmed in the mixed-effects modeling analysis with age as a fixed effect and δ as a model parameter. The model regressing traversed distance on age revealed a significant age effect ($b_{\mathrm{Age}} = -1.00$, $t_{18} = -4.72$, $p < .01$) and a significant inverse relation between error variance and age ($\delta = -.69$, $\chi^2_1 = 12.6$, $p < .01$).

Straightness of Hand Trajectory

Previous work on reaching (Berthier & Keen, 2006) has shown that infants qualitatively change the way they move their hands through space as they get older. Young infants frequently exhibit circuitous hand paths whereas older infants are far more efficient in their movements and adopt straight-line hand trajectories when reaching for a target. To investigate the corresponding possibility in the control of object banging, we analyzed the straightness ratio of the hand, defined as the total

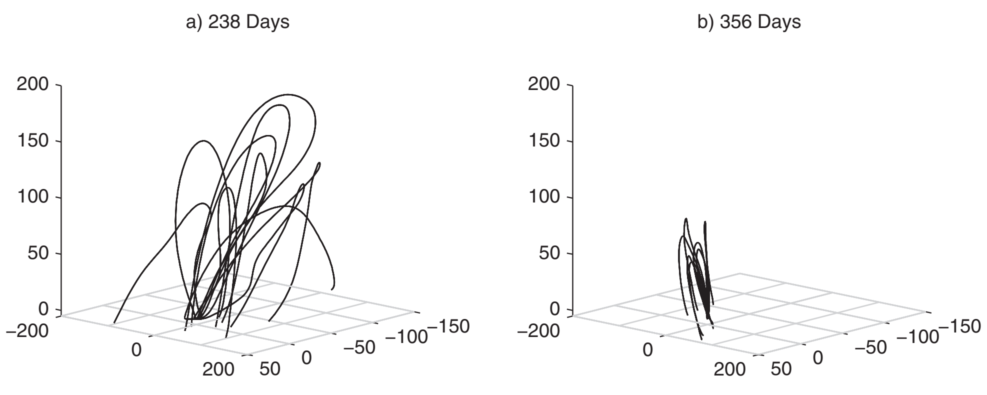

Figure 2. Examples of representative hand trajectories for a young infant (a) 238 days old, and an older infant (b) 356 days old. All available strikes for each infant, 10 and 7, respectively, are presented and starting locations for each strike are normalized to be at the origin.

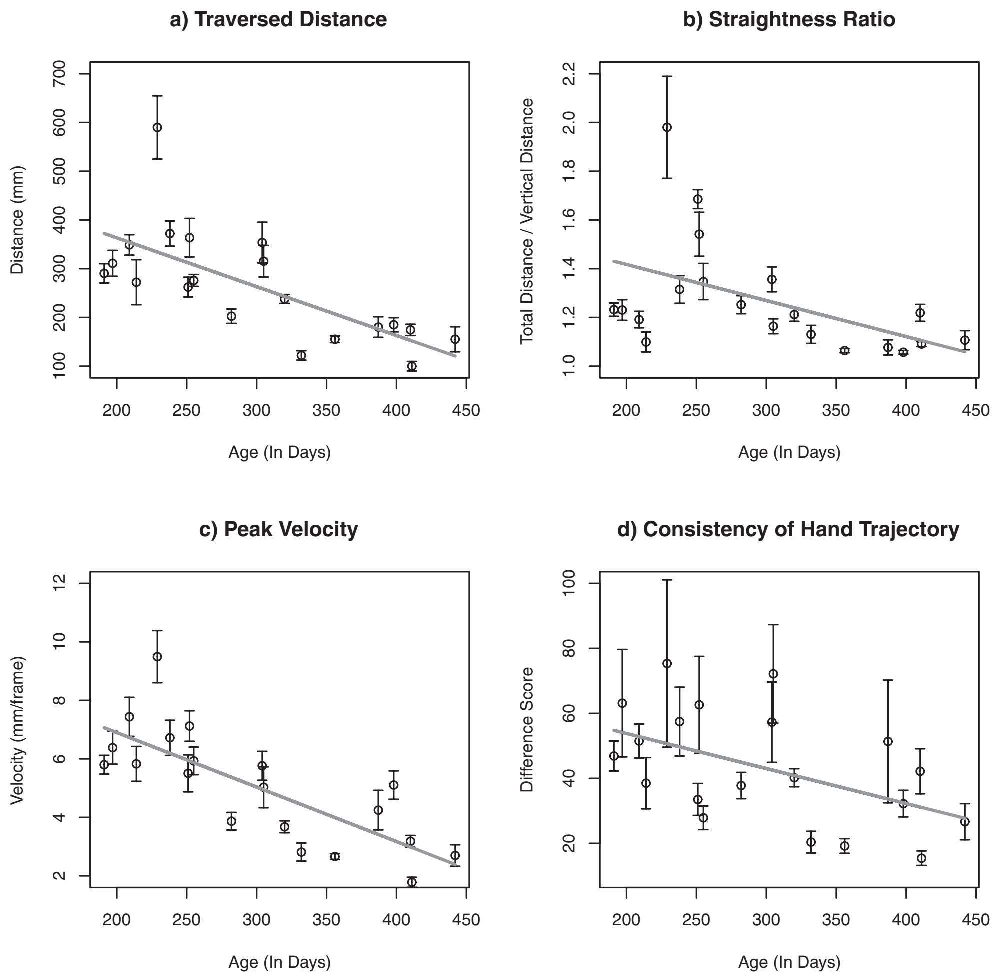

Figure 3. The figures show the changes that occur in infants' hand trajectories as they get older. With increasing age, infants move their hands less (a), in a straighter up and down trajectory (b), at lower velocities (c), and in a more consistent fashion from one strike to the next (d). Depicted are the mean and standard error for each infant as well as the predicted values from the mixed-effects models (solid line).

distance traversed divided by the vertical distance traversed for each individual strike.

The mixed-effects modeling analysis with age as a fixed effect, δ as a model parameter and straightness ratio as the dependent variable yielded a significant effect of age ($b_{\text{Age}} = -.001$, $t_{18} = -3.27$, $p < .01$). Older infants as compared to younger ones moved their hands in a straighter up and down path when striking the object against the table (see Figures 2 and 3b). In addition, older infants were less variable than younger infants, as indicated by the significant effect of heteroscedasticity and negative δ value ($\delta = -1.34$, $\chi^2_1 = 44.04$, $p < .001$).

Peak Velocity of the Hand

Kinetic energy is a measure of the potential amount of force that infants are applying during a strike (Liu et al., 2009) and defined as $E_k = ½ \text{ Mass} \times \text{Velocity}^2$, but since mass is a constant, the only variable in this formula is velocity. Peak velocity was always achieved directly prior to impact in our sample and can thus be taken as a direct indicator of kinetic energy for a given strike. To examine developmental changes in the potential amount of force that infants apply when banging a handled object, we regressed the peak velocity for each strike onto age using a mixed-effects model with age as a fixed effect and δ as a model parameter. Results show a clear decrease in peak velocity as infants get older ($b_{\text{Age}} = -.02$, $t_{18} = -5.20$, $p < .001$; see Figure 3c). Furthermore, there was significant heteroscedasticity with older infants being less variable than younger ones ($\delta = -.61$, $\chi^2_1 = 9.89$, $p < .01$), suggesting that older infants are more consistent in the amount of force they produce from strike to strike.

Within Bout Consistency

The previous analyses addressed overall levels of variability as a function of age across all strikes irrespective of the bout from which they came. However, it might be the case that younger infants evidence consistent patterns *within* a bout of banging. To address this issue, we analyzed how consistent corresponding points of the hand trajectories were from one strike to the next within the same bout. We time-normalized all strikes to consist of 100 frames and computed the Euclidean distance (in mm) of the hand position at one strike to the immediately following strike at each standardized frame. The average distance between corresponding points in a strike across all 100 frames is our measure for within bout consistency of hand movements.

The mixed-effects model with age as a fixed effect revealed a significant effect of age ($b_{Age} = -.11$, $t_{18} = -2.60$, $p < .05$). Even at corresponding time points between sequential strikes within a bout, younger infants' hand trajectories varied greatly, whereas older infants showed a high degree of consistency (see Figures 2 and 3d).

Discussion

The results of this study offer new insights into the motor origins of tool use. The findings indicate that banging, a common manual behavior displayed by infants (Thelen, 1981), transitions during the second half-year into a form of action that is preadapted for tool use, well before children have gained extensive experience with hammers or similar pounding instruments.

In the current study, infants between 6 and 15 months of age were presented hammer-like objects on a tabletop surface. We used high-speed motion tracking cameras to examine the kinematics of infants' arm and hand movements as they banged these objects. Results indicated that the younger infants banged the objects inefficiently: Their hand movements covered greater distances and traveled circuitous paths at high velocities relative to older infants. Similarly, younger infants banged the objects in an inconsistent manner: Their hand trajectories varied greatly in terms of the amount of distance traversed, straightness and peak velocity. Furthermore, younger infants' hand trajectories were inconsistent even within individual bouts of banging, from one temporally adjacent strike to the next.

By contrast, older infants exhibited many of the motor characteristics that would be expected of a skilled tool user. Their hand trajectories were both efficient and consistent. By around 1 year of age, infants showed straight up and down hand trajectories of consistent length, at a consistent velocity, which varied very little from one strike to the next. Equally important, these characteristics were manifested not just within individual bouts of banging, but across bouts as well, suggesting that this more skilled form of banging had indeed become stable. Thus, at the end of the 1st year infants fulfill the prerequisite criteria for instrumental hammering: Their movements are regular and predictable, they are capable of controlling the amount of force they apply, and they move their hands straight up and down enabling the best possible aim.

The changes in motor behavior that occur between 6 and 15 months are especially noteworthy because infants at these ages do not typically engage in instrumental tool use with hammers or other pounding implements (Gesell, 1940). The observed changes here are therefore presumably driven by infants' experiences while using banging to explore and act on objects they encounter in their everyday activities. The exact nature of the developmental changes we observed fits precisely with the predictions by minimum theories: Infants become more consistent and efficient as they repeatedly engage in banging behaviors. We hypothesize that as a result of becoming efficient and consistent, infants can subsequently recruit the same behavior pattern for adaptive and functional ends.

Infants' exploratory banging behaviors and their apparent utility for later instrumental percussive tool use are also noteworthy given the evolutionary and phylogenetic record of humans and our primate relatives. For nearly all of human tool-using history, implements requiring percussive action, like hammer stones and stone axes, have figured prominently in the human tool kit (Ambrose, 2001; Schick & Toth, 1993). Similarly, percussive tools are used by chimpanzees and capuchin monkeys, species whose juveniles are known to engage in exploratory banging behaviors similar to that of human infants (de Resende, Ottoni, & Fragaszy, 2008; Hayashi, Takeshita, & Matsuzawa, 2006; Inoue-Nakamura & Matsuzawa, 1997). We believe that it is no coincidence that percussive tool use and exploratory banging behaviors frequently co-occur in species where such tools are employed. The nature of developmental change during exploratory banging creates ideal conditions for instrumental tool use in humans and perhaps other primates as well.

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